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Maurer et al.

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(54) **SHELL-AND-TUBE HEAT EXCHANGERS WITH FOAM HEAT TRANSFER UNITS**

(75) Inventors: **Scott M. Maurer**, Haymarket, VA (US); **Nicholas J. Nagurny**, Manassas, VA (US); **Michael R. Eller**, New Orleans, LA (US); **James W. Klett**, Knoxville, TN (US)

(73) Assignee: **Lockheed Martin Corporation**, Bethesda, MD (US)

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Related U.S. Application Data

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(51) **Int. Cl.**
F28D 7/16 (2006.01)
F28D 7/02 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***F28D 7/1607*** (2013.01); ***F28D 7/024*** (2013.01); ***F28D 7/1669*** (2013.01); ***F28F 9/22*** (2013.01);
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(58) **Field of Classification Search**
CPC F28D 3/02; F28D 3/04; F28D 7/1607; F28D 7/024; F28D 7/1669; F28F 9/22; F28F 21/02; F28F 13/003; F28F 2009/226; F28F 2275/025; F28F 2275/062
USPC 165/159, 160, 162, 905
See application file for complete search history.

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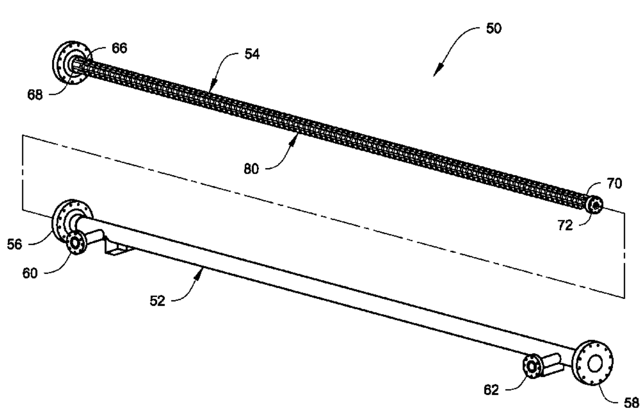
Primary Examiner — Tho V Duong
Assistant Examiner — Raheena Rehman
(74) *Attorney, Agent, or Firm* — Withrow & Terranova, PLLC

(57) **ABSTRACT**

Shell-and-tube heat exchangers that utilize one or more foam heat transfer units engaged with the tubes to enhance the heat transfer between first and second fluids. The foam of the heat transfer units can be any thermally conductive foam material that enhances heat transfer, for example graphite foam. These shell-and-tube heat exchangers are highly efficient, inexpensive to build, and corrosion resistant. The described heat exchangers can be used in a variety of applications, including but not limited to, low thermal driving force applications, power generation applications, and non-power generation applications such as refrigeration and cryogenics. The foam heat transfer units can be made from any thermally conductive foam material including, but not limited to, graphite foam or metal foam. In an embodiment, the heat exchanger utilizes tubes that are twisted around a central foam heat transfer unit.

10 Claims, 13 Drawing Sheets



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F28F 9/22 (2006.01)
F28F 13/00 (2006.01)
F28F 21/02 (2006.01)

(52) **U.S. Cl.**
CPC ***F28F 13/003*** (2013.01); ***F28F 21/02*** (2013.01); *F28F 2009/226* (2013.01); *F28F 2275/025* (2013.01); *F28F 2275/062* (2013.01)

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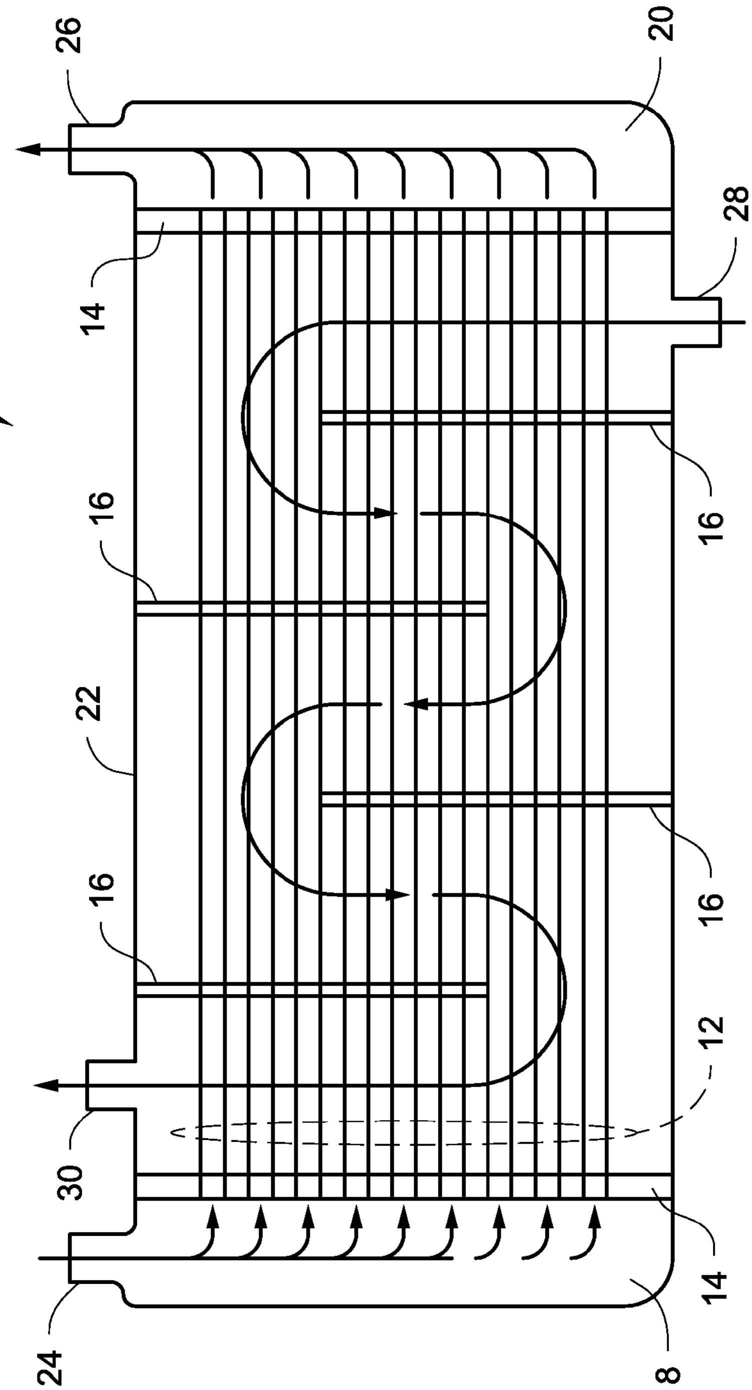

Fig. 1
(Prior Art)

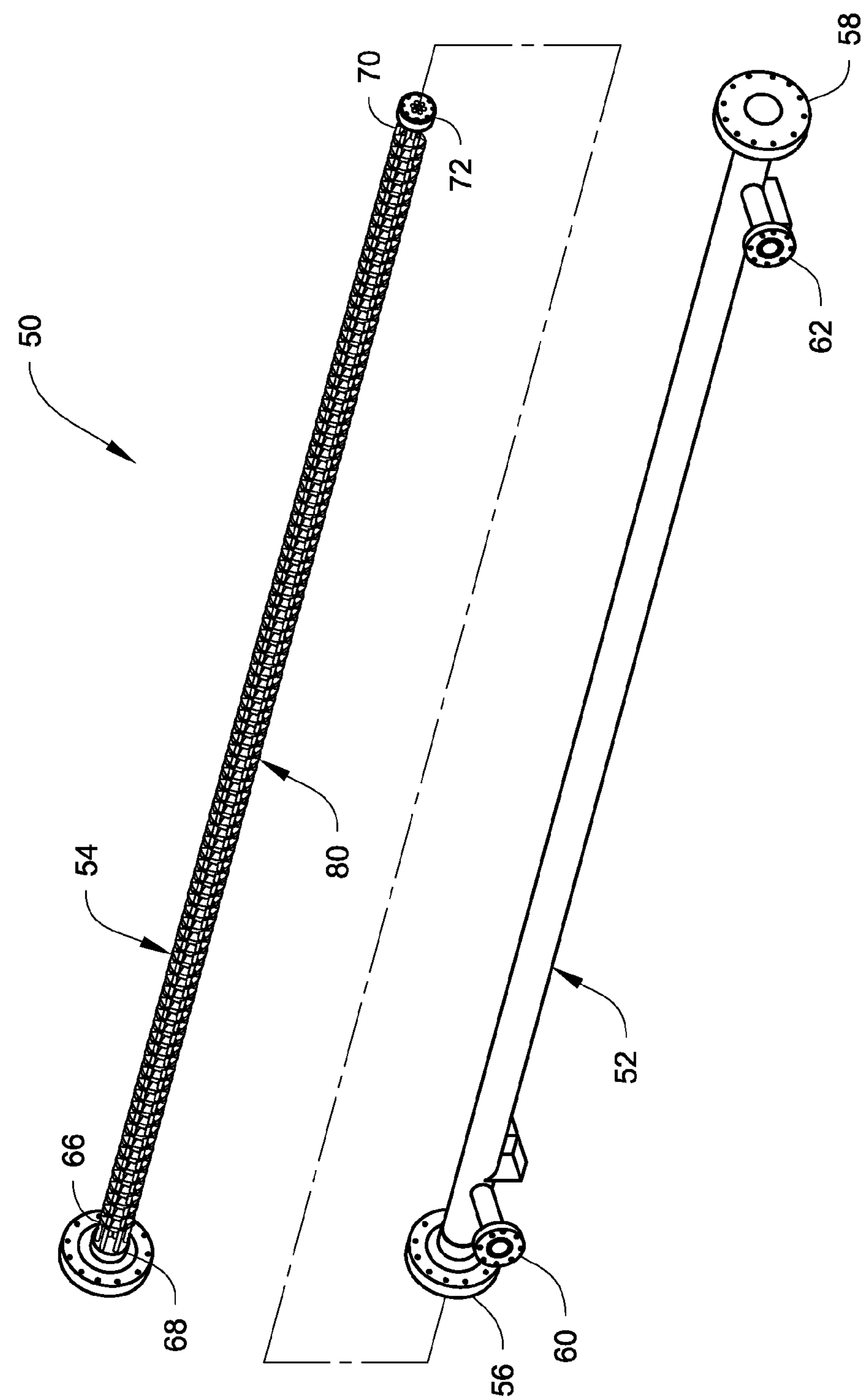

Fig. 2

Fig. 3

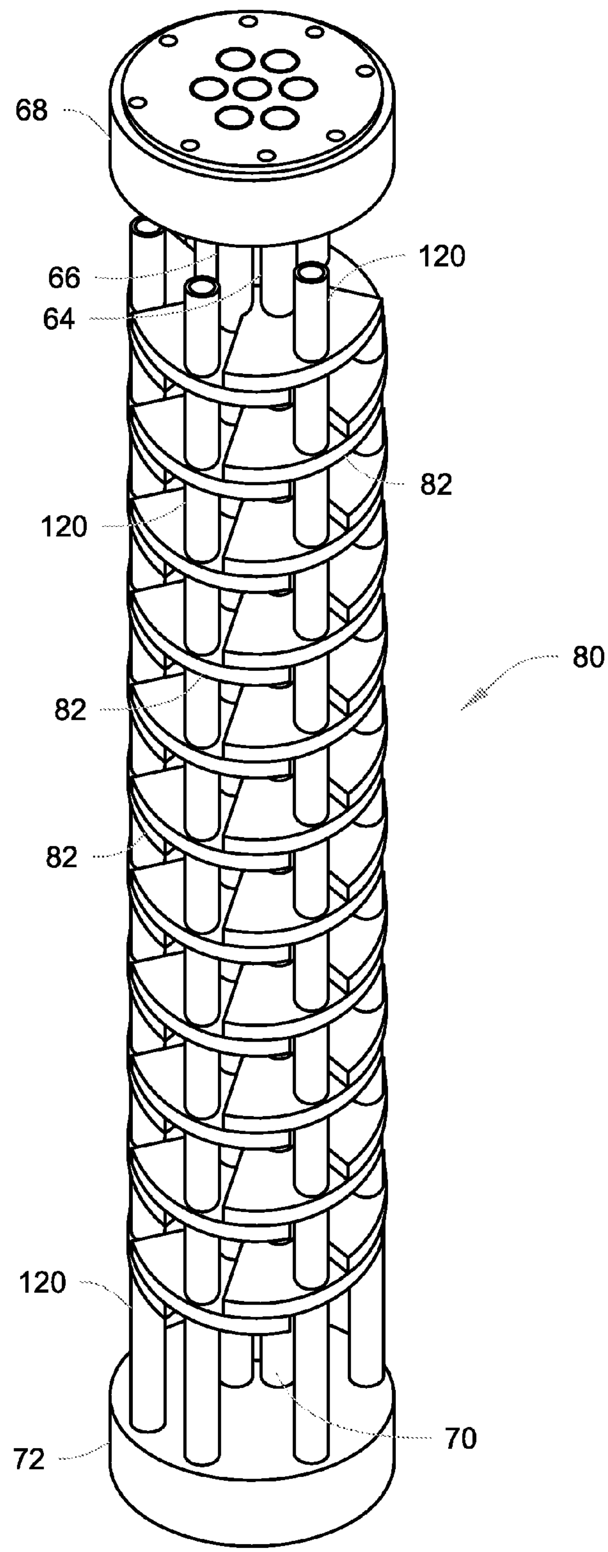

Fig. 4

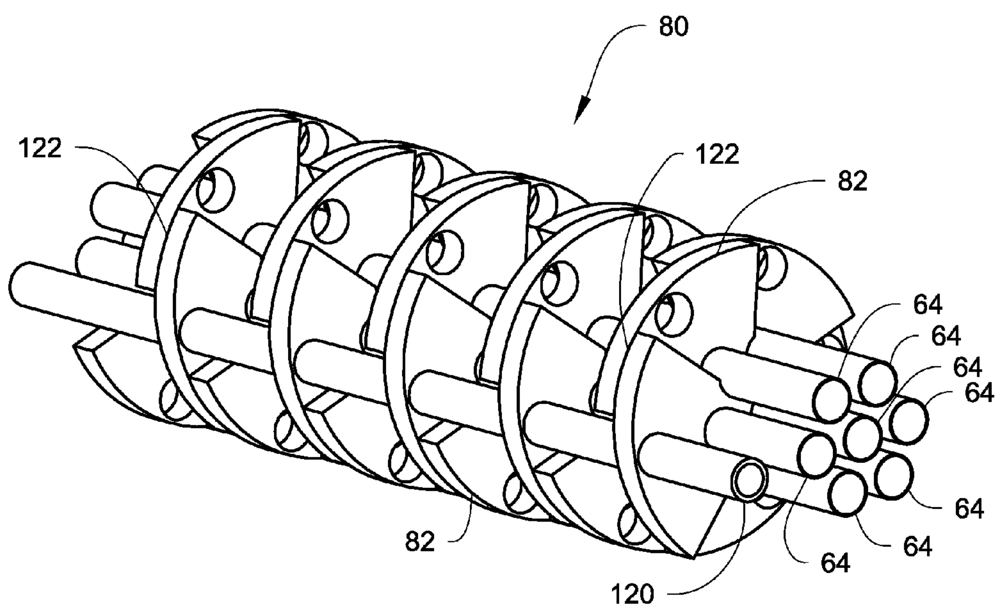
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Fig. 5

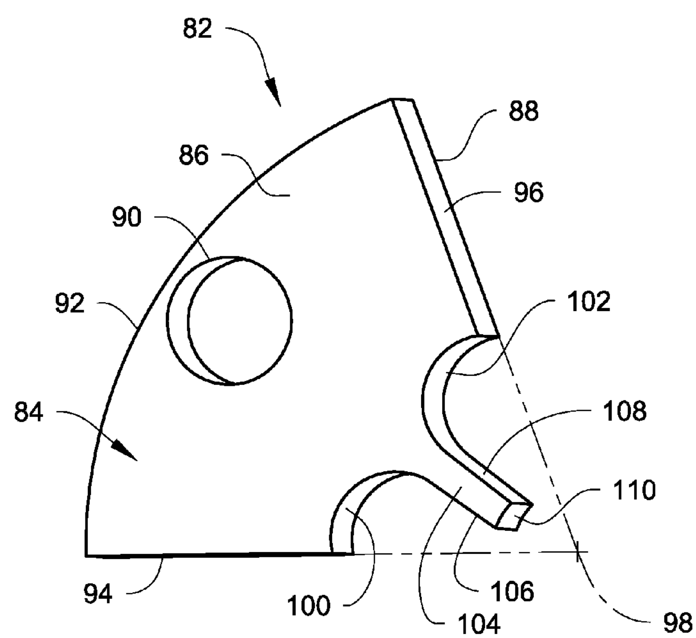
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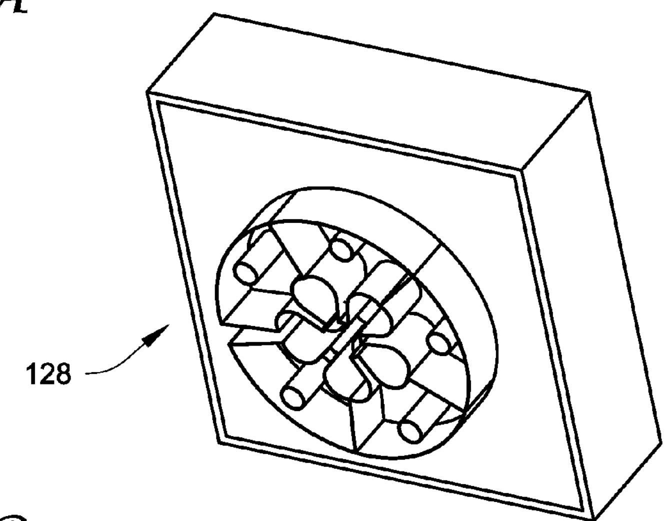
Fig. 6A



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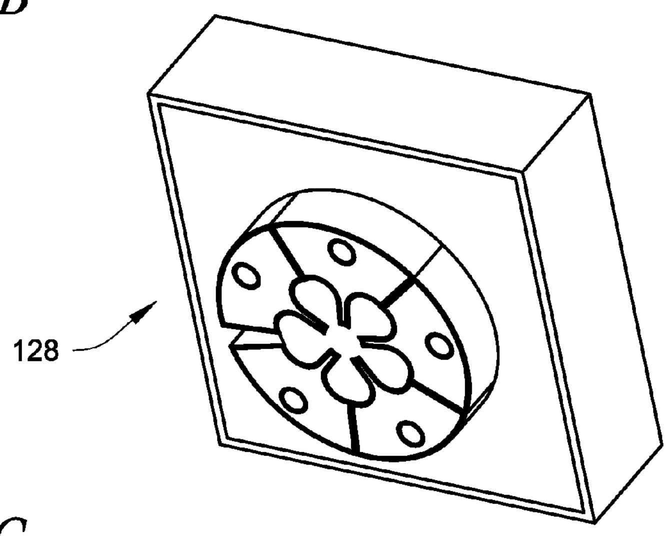

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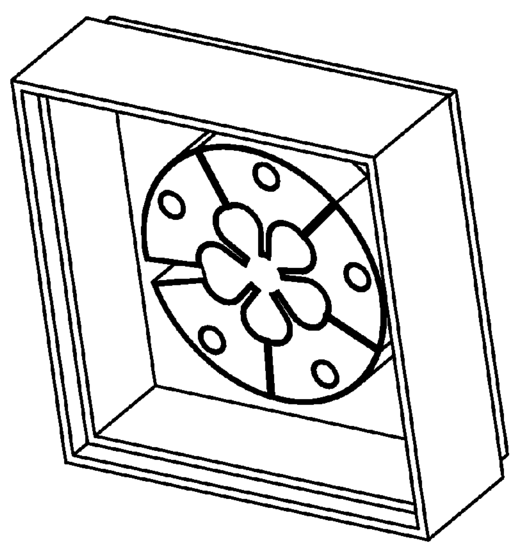

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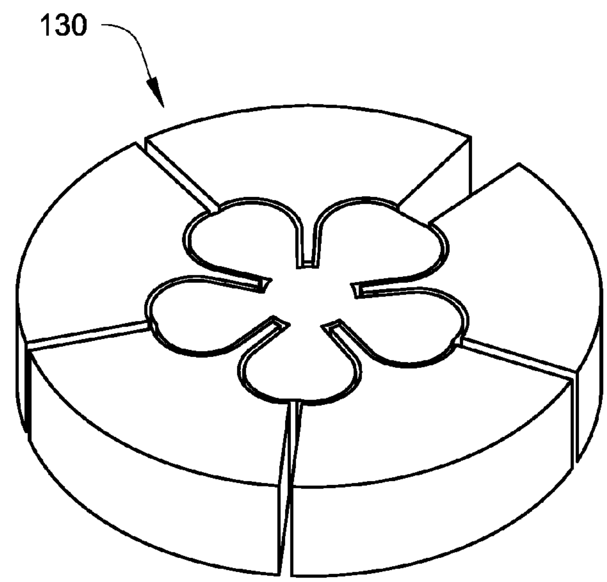

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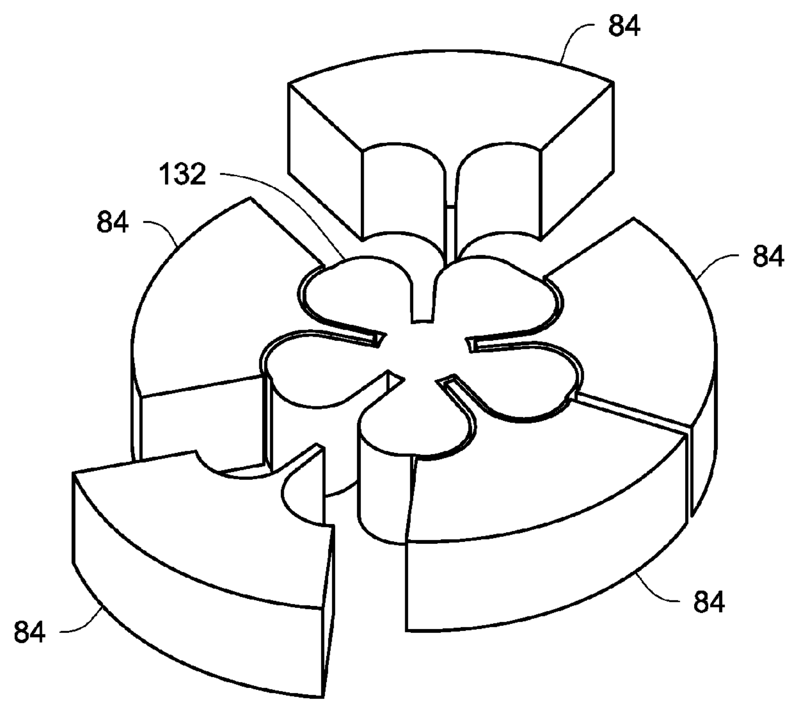


Fig. 7

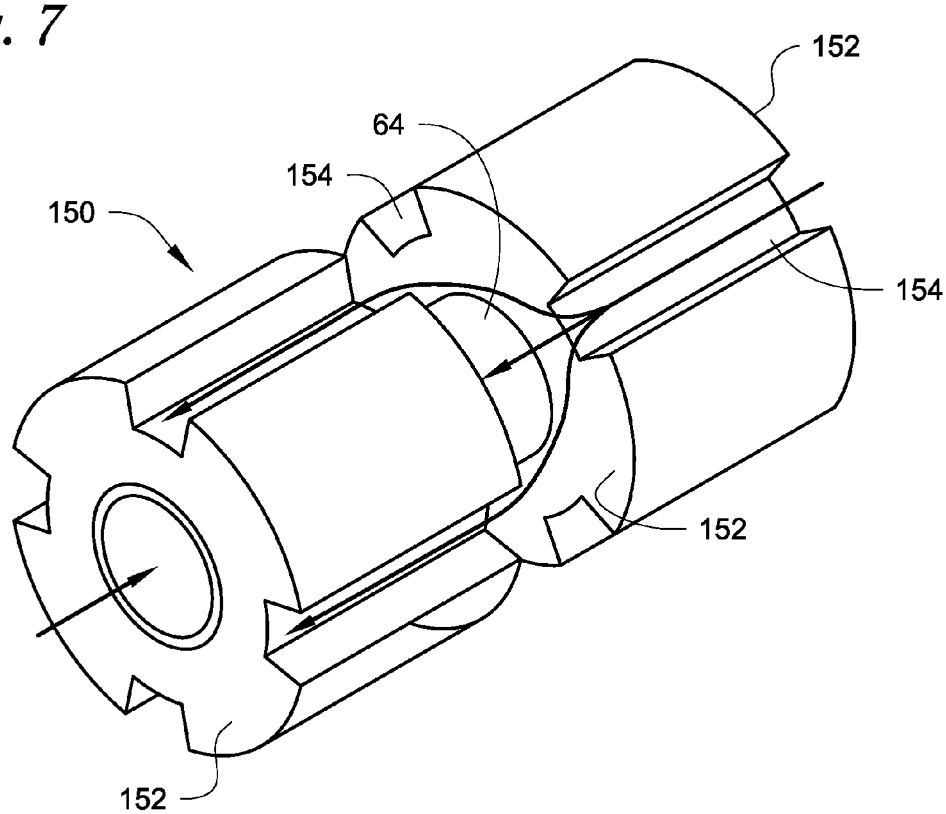
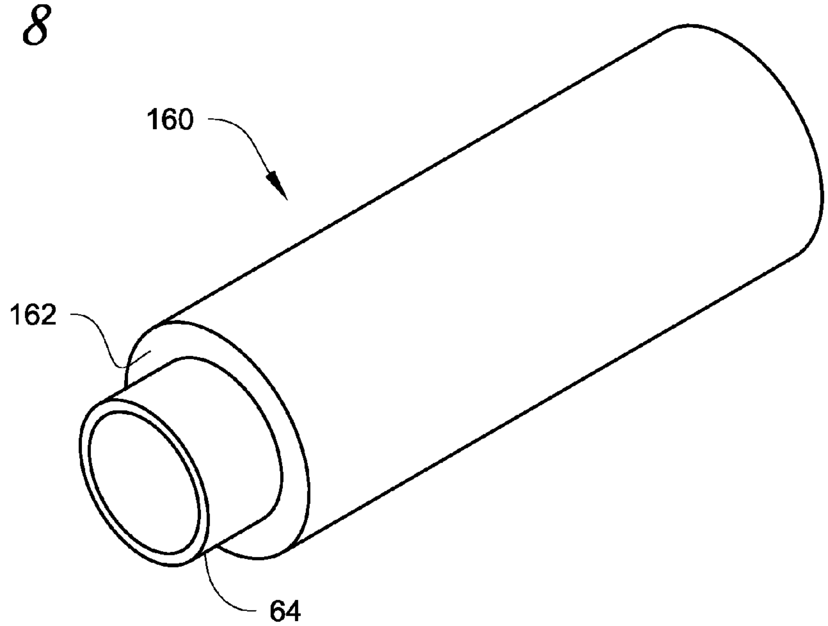


Fig. 8



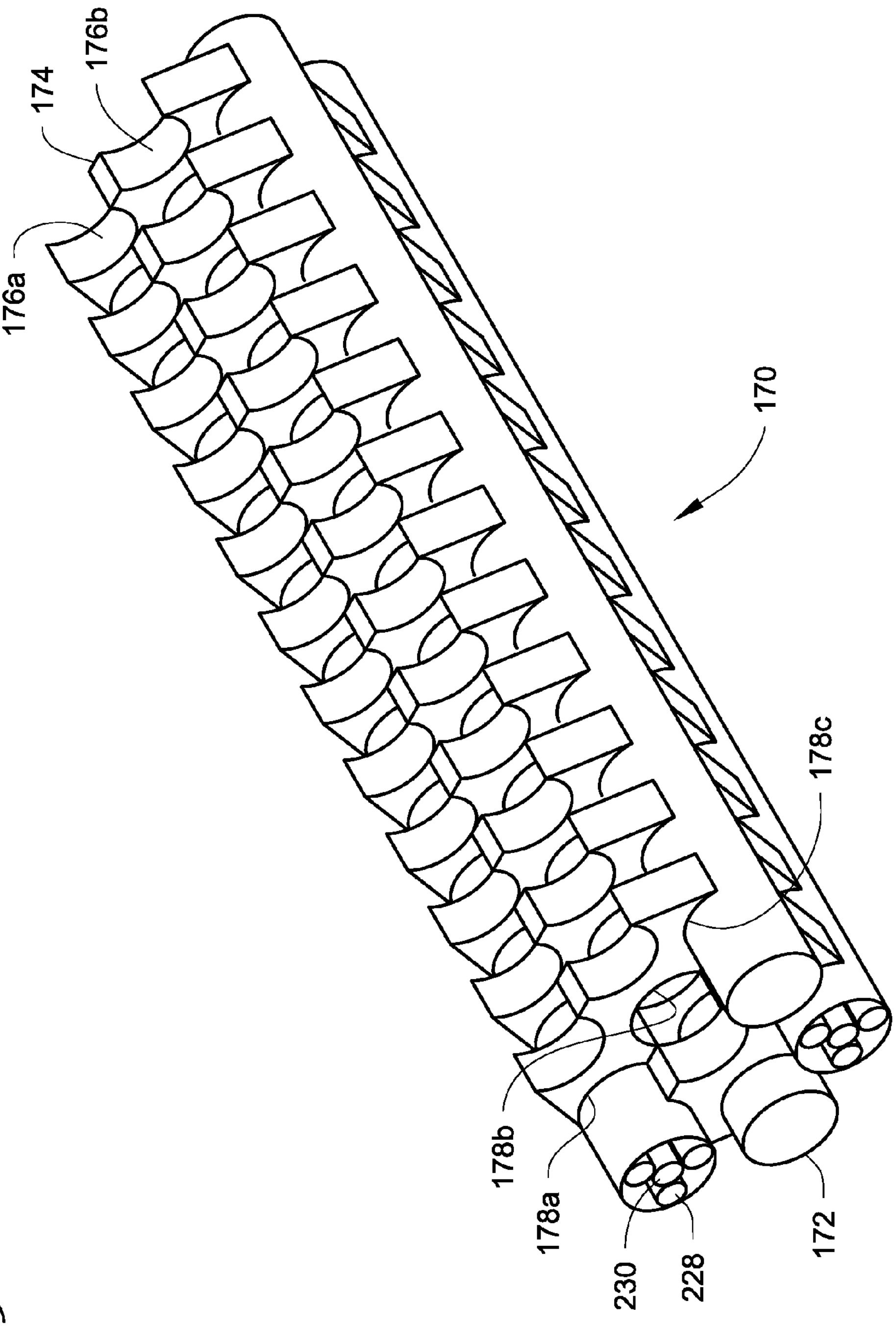


Fig. 9

Fig. 10A

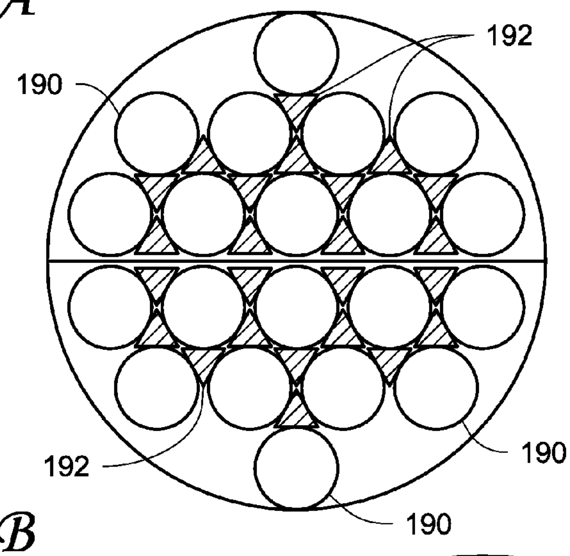


Fig. 10B

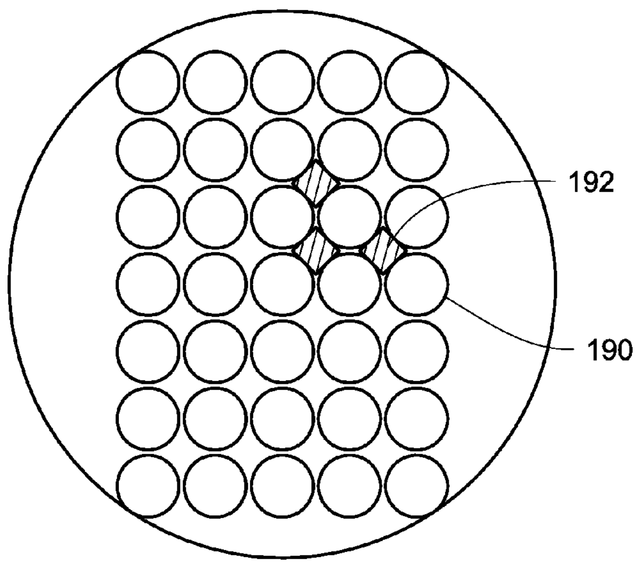
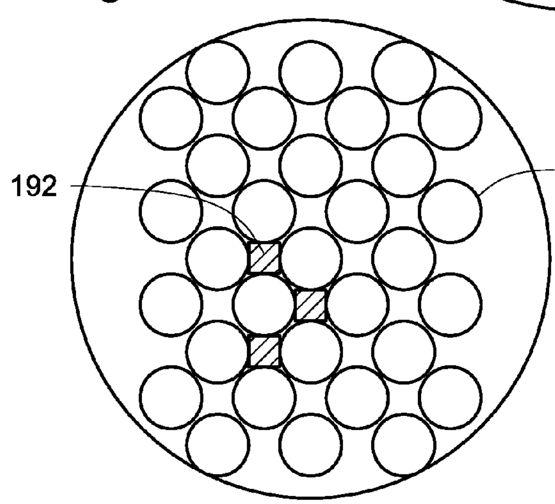
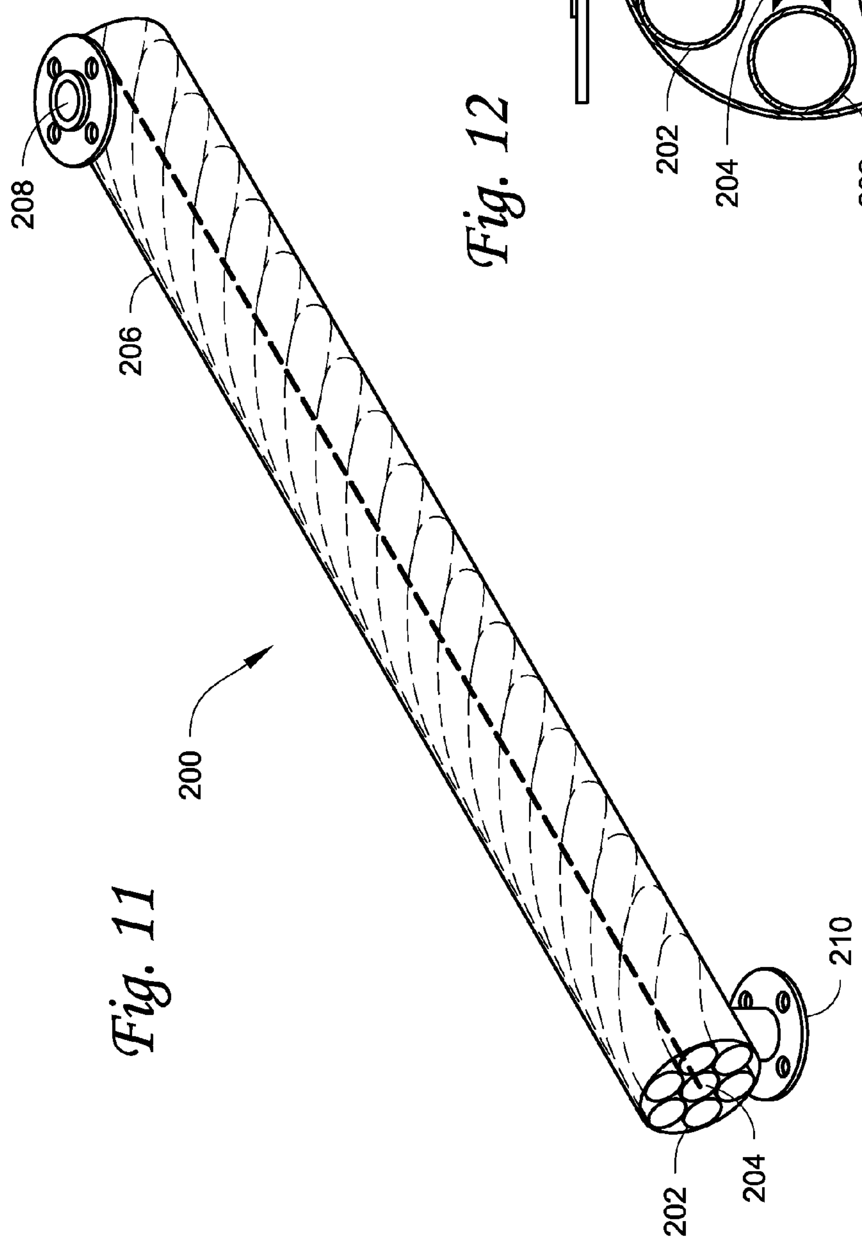


Fig. 10C





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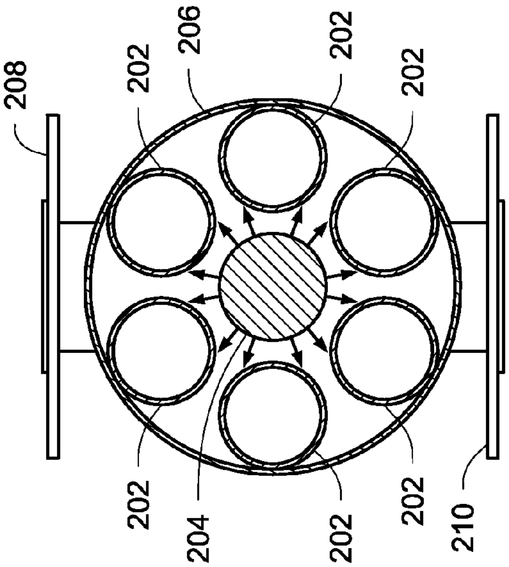

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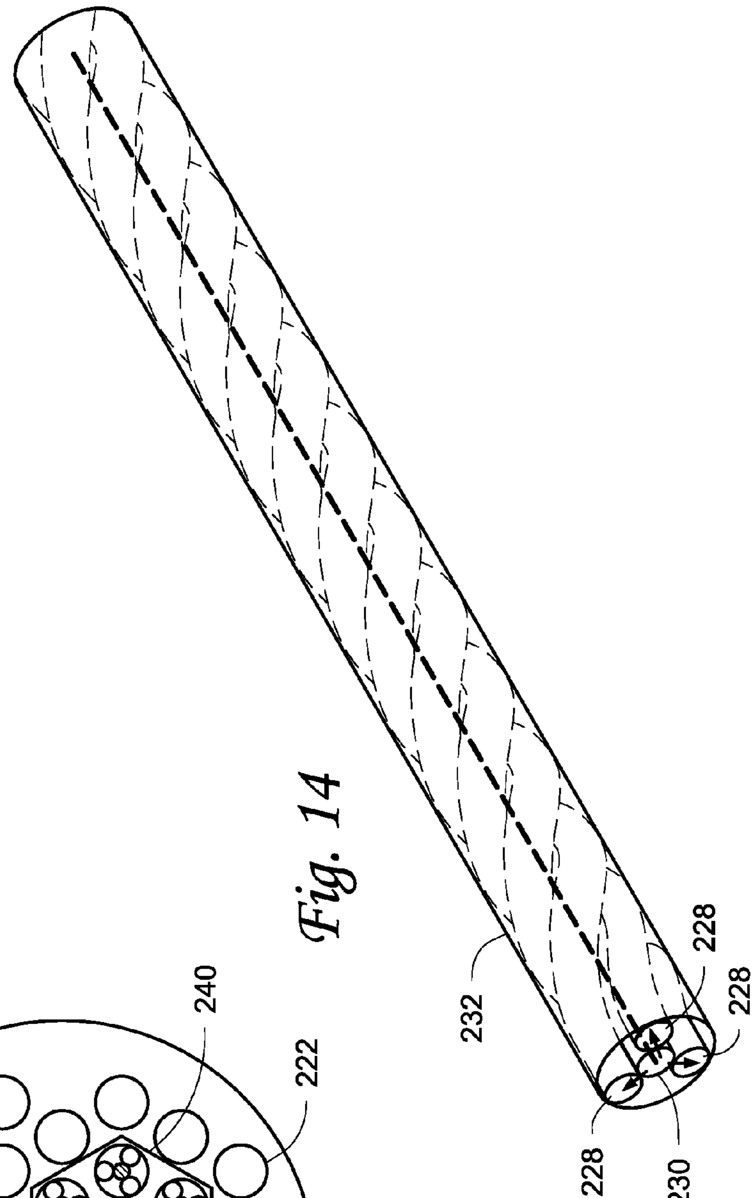

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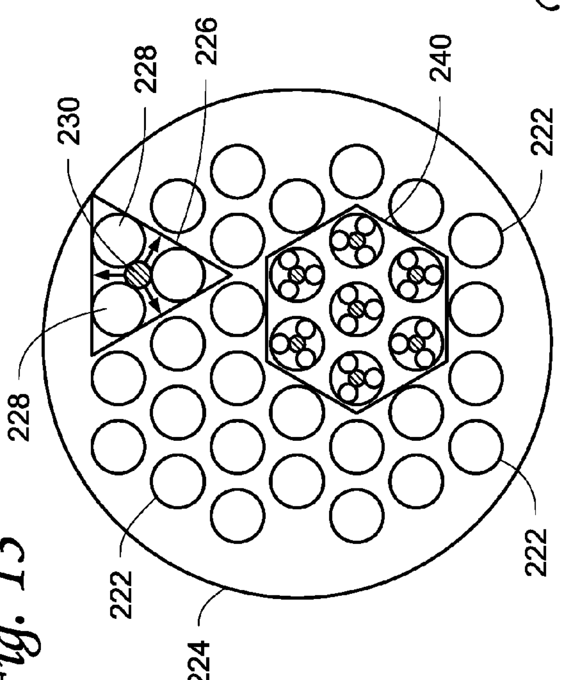


Fig. 13

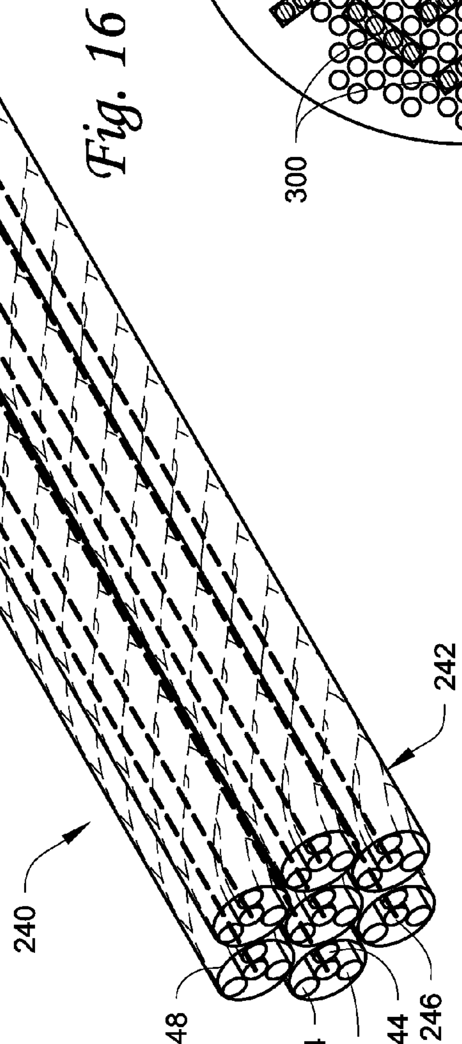


Fig. 15

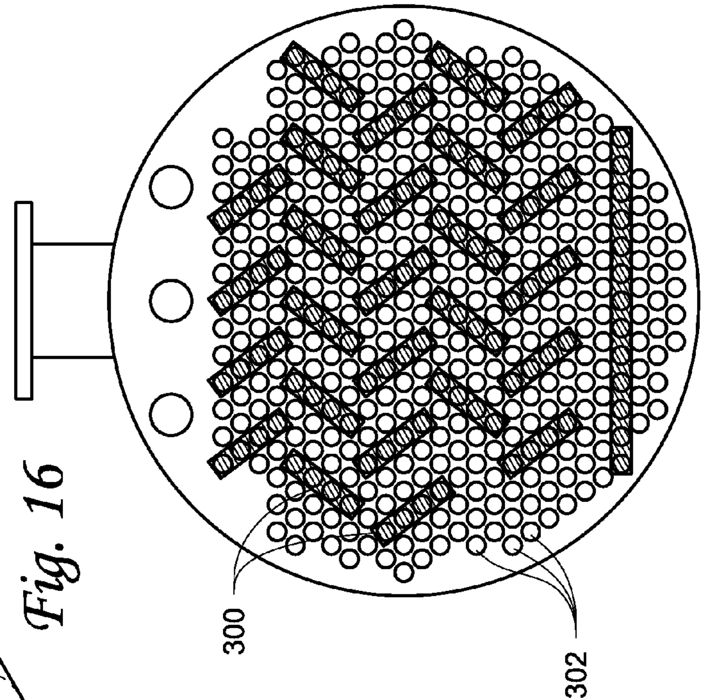


Fig. 16

Fig. 17A

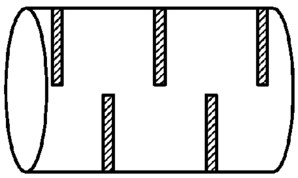


Fig. 17B

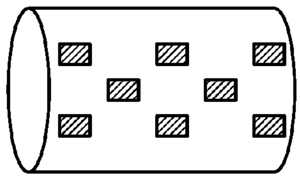


Fig. 17C

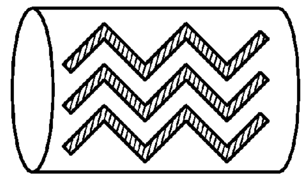


Fig. 17D

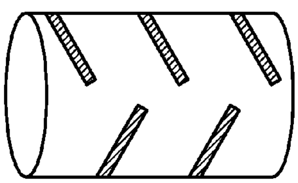


Fig. 17E

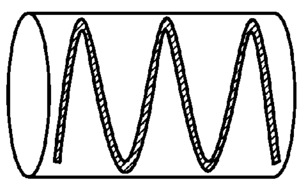


Fig. 17F

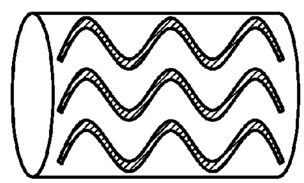
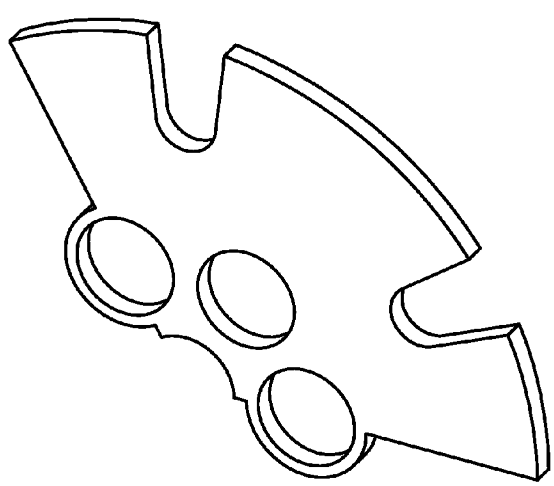


Fig. 18



SHELL-AND-TUBE HEAT EXCHANGERS WITH FOAM HEAT TRANSFER UNITS

This application claims the benefit of U.S. Provisional Applicant Ser. No. 61/439,564, filed on Feb. 4, 2011, the entire contents of which are incorporated herein by reference.

FIELD

This disclosure relates to heat exchangers in general, and, more particularly, to heat exchangers, including but not limited to shell-and-tube heat exchangers, employing heat conducting foam material.

BACKGROUND

Heat exchangers are used in many different types of systems for transferring heat between fluids in single phase, binary or two-phase applications. An example of a commonly used heat exchanger is a shell-and-tube heat exchanger. Generally, a shell-and-tube heat exchanger includes multiple tubes placed between two tube sheets and encapsulated in a shell. A first fluid is passed through the tubes and a second fluid is passed through the shell such that it flows past the tubes separated from the first fluid. Heat energy is transferred between the first fluid and second fluid through the walls of the tubes.

A shell-and-tube heat exchanger is considered the primary heat exchanger in industrial heat transfer applications since they are economical to build and operate. However, shell-and-tube heat exchangers are not generally known for having high heat transfer efficiency.

SUMMARY

Shell-and-tube heat exchangers are described that utilize one or more foam heat transfer units engaged with the tubes to enhance the heat transfer between first and second fluids. The foam of the heat transfer units can be any thermally conductive foam material that enhances heat transfer, for example graphite foam. The shell-and-tube heat exchangers described herein are highly efficient, inexpensive to build, and corrosion resistant. The described heat exchangers can be used in a variety of applications, including but not limited to, low thermal driving force applications, power generation applications, and non-power generation applications such as refrigeration and cryogenics. The foam heat transfer units can be made from any thermally conductive foam material including, but not limited to, graphite foam or metal foam.

In one embodiment, a heat exchanger includes a tube having a central axis and an outer surface. A heat transfer unit is connected to and in thermal contact with the outer surface of the tube, with the heat transfer unit having a heat transfer surface extending substantially radially from the outer surface of the tube. The heat transfer unit includes graphite foam. For example, the heat transfer can consist essentially of, or consist of, graphite foam.

In another embodiment, a heat exchanger includes a tube bundle having a central axis and a plurality of tubes for conveying a first fluid. A first tube sheet and a second tube sheet are provided, and each of the tubes includes a first end joined to the first tube sheet in a manner to prevent fluid leakage between the first end and the first tube sheet and a second end joined to the second tube sheet in a manner to prevent fluid leakage between the second end and the second tube sheet. A heat transfer unit is connected to and in thermal contact with the tubes, with the heat transfer unit consisting essentially of graphite foam.

One suitable method for connecting the tubes and the tube sheets is friction-stir-welding (FSW). The use of FSW is particularly beneficial in heat exchanger applications subject to corrosive service, since the FSW process eliminates seams, no dissimilar metals are used and, in the case of saltwater environments, no galvanic cell is created.

In another embodiment, the heat transfer unit is in the form of a generally radiused and wedge-shaped, planar body that consists essentially of foam material, for example graphite foam. The body includes first and second opposite major surfaces, a support rod hole or cut-out extending through the body from the first major surface to the second major surface, an arcuate radially outer edge connected to linear side edges at opposite ends of the outer edge, and at least two tube contact surfaces opposite the radially outer edge. In other embodiments, the heat transfer units can be a combination of radiused and triangular or square shaped to fit in the pitch space between tubes. All of the heat transfer units described herein can be used by themselves or together in various combinations that one finds suitable to increase the heat transfer efficiency of the heat exchanger.

In an embodiment, the tubes can be twisted around a foam heat transfer unit. In addition, each tube can be twisted around its own axis to further increase heat transfer efficiency.

The tubes of the shell-and-tube heat exchangers described herein can be arranged in numerous patterns and pitches, including but not limited to, an equilateral triangular pattern defining a triangular pitch between tubes, a square pattern defining a square pitch between tubes, and a staggered square pattern defining a square or diamond pitch between tubes.

The shell-and-tube heat exchangers described herein can also be configured to have any desired flow configuration, including but not limited to, cross-flow, counter-current flow, and co-current flow. In addition, the tubes can have any desired tube layout/configuration including, but not limited to, single pass and multi-pass. Further, the shell, tubes, tube sheets, and other components of the described heat exchangers can be made of any materials suitable for the desired application of the heat exchanger including, but not limited to, metals such as aluminum, titanium, copper and bronze, steels such as carbon steel and high alloy stainless steels, and non-metals such as plastics, fiber-reinforced plastics, thermally enhanced polymers, and thermoplastics.

DRAWINGS

FIG. **1** shows a conventional shell-and-tube heat exchanger.

FIG. **2** is an exploded view of an improved shell-and-tube heat exchanger described herein.

FIG. **3** illustrates a tube bundle for the shell-and-tube heat exchanger of FIG. **2**.

FIG. **4** is a partial view of the tube bundle of FIG. **3**.

FIG. **5** illustrates a foam heat transfer unit used with the tube bundle of FIGS. **2**-**4**.

FIGS. **6**A-E illustrate an exemplary process of forming the heat transfer unit of FIG. **5**.

FIG. **7** illustrates another example of a foam heat transfer unit useable with the tube bundle.

FIG. **8** illustrates still another example of a foam heat transfer unit.

FIG. 9 illustrates still another example of a foam heat transfer unit.

FIG. 10A is a cross-sectional view of a tube bundle with another example of a foam heat transfer unit.

FIGS. 10B and 10C illustrate additional examples of tube patterns for tube bundles.

FIG. 11 illustrates an example of an improved shell-and-tube heat exchanger that employs twisted tubes together with a foam heat transfer unit.

FIG. 12 is a cross-sectional view of the shell-and-tube heat exchanger of FIG. 11.

FIG. 13 is a cross-sectional view of another implementation of twisted tubes and foam heat transfer units.

FIG. 14 illustrates details of the portion within the triangle in FIG. 13.

FIG. 15 illustrates details of the portion within the hexagon in FIG. 13.

FIG. 16 is a cross-sectional view of an improved shell-and-tube heat exchanger that employs an additional example of foam heat transfer units.

FIGS. 17A-F illustrate examples of patterns formed by different configurations of foam heat transfer units.

FIG. 18 shows an example of a plate that can be used to strengthen a heat transfer unit.

DETAILED DESCRIPTION

FIG. 1 shows a conventional shell-and-tube heat exchanger **10** that is configured to exchange heat between a first fluid and a second fluid in a single-pass, primarily counter-flow (the two fluids flow primarily in opposite directions) arrangement. The heat exchanger **10** has tubes **12**, a tube sheet **14** at each end of the tubes, baffles **16**, an input plenum **18** for a first fluid, an output plenum **20** for the first fluid, a shell **22**, an inlet **24** to the input plenum for the first fluid, and an outlet **26** from the output plenum for the first fluid. In addition, the shell **22** includes an inlet **28** for a second fluid and an outlet **30** for the second fluid.

The first fluid and the second fluid are at different temperatures. For example, the first fluid can be at a lower temperature than the second fluid so that the second fluid is cooled by the first fluid.

During operation, the first fluid enters through the inlet **24** and is distributed by the manifold or plenum **18** to the tubes **12** whose ends are in communication with the plenum **18**. The first fluid flows through the tubes **12** to the second end of the tubes and into the output plenum **20** and then through the outlet **26**. At the same time, the second fluid is introduced into the shell **22** through the inlet **28**. The second fluid flows around and past the tubes **12** in contact with the outer surfaces thereof, exchanging heat with the first fluid flowing through the tubes **12**. The baffles **16** help increase the flow path length of the second fluid, thereby increasing the interaction and residence time between the second fluid in the shell-side and the walls of tubes. The second fluid ultimately exits through the outlet **30**.

Turning to FIGS. **2-4**, an improved shell-and-tube heat exchanger **50** is illustrated. The heat exchanger is illustrated as a single-pass, primarily counter-flow (the two fluids flow primarily in opposite directions) arrangement. However, it is to be realized that the heat exchanger **50** could also be configured as a multi-pass system, as well as for cross-flow (the two fluids flow primarily generally perpendicular to one another), co-current flow (the fluids primarily flow in the same directions), or the two fluids flow can flow at any angle therebetween.

The heat exchanger **50** includes a shell **52** and a tube bundle **54** that is configured to be disposable in the shell **52**. In the illustrated embodiment, the shell **52** includes an axial inlet **56** at a first end for introducing a first fluid and an axial outlet **58** at the opposite second end for the first fluid. In addition, the shell includes a radial inlet **60** near the first end for introducing a second fluid and a radial outlet **62** near the second end for the second fluid.

The shell **52** is configured to enclose the tube bundle **54** and constrain the second fluid to flow along the surfaces of tubes in the tube bundle. The shell **52** can be made of any material that is suitably resistant to corrosion or other effects from contact with the type of second fluid being used, as well as be suitable for the environment in which the heat exchanger **50** is used. For example, the shell can be made of a metal including, but not limited to, steel or aluminum, or from a non-metal material including, but not limited to, a plastic or fiber-reinforced plastic.

The tube bundle **54** extends substantially the length of the shell and includes a plurality of hollow tubes **64** for conveying the first fluid through the heat exchanger **50**. The tubes **64** are fixed at a first end **66** to a first tube sheet **68** and fixed at a second end **70** to a second tube sheet **72**. As would be understood by a person of ordinary skill in the art, the tube sheets **68**, **72** are sized to fit within the ends of the shell **52** with a relatively close fit between the outer surfaces of the tube sheets and the inner surface of the shell. When the tube bundle **54** is installed inside the shell **52**, the tube sheets of the tube bundle and the shell collectively define an interior chamber that contains the tubes **64** of the tube bundle. The radial inlet **60** and radial outlet **62** for the second fluid are in fluid communication with the interior chamber. Due to the closeness of the fit and/or through additional sealing, leakage of the second fluid from the interior chamber of the shell past the interface between the outer surfaces of the tube sheets **68**, **72** and the inner surface of the shell is prevented.

As shown in FIG. **3**, the ends of the tubes **64** penetrate through the tube sheets **68**, **72** via holes in the tube sheets so that inlets/outlets of the tubes are provided on the sides of the tube sheets facing away from the interior chamber of the shell. The ends of the tubes **64** may be attached to the tube sheets in any manner to prevent fluid leakage between the tubes **64** and the holes through the tube sheets. In one example, the ends of the tubes are attached to the tube sheets by FSW. The use of FSW is particularly beneficial where the heat exchanger is used in an environment where it is subject to corrosion, since the FSW process eliminates seams, no dissimilar metals are used and, in the case of saltwater environments, no galvanic cell is created.

FSW is a known method for joining elements of the same material. Immense friction is provided to the elements such that the immediate vicinity of the joining area is heated to temperatures below the melting point. This softens the adjoining sections, but because the material remains in a solid state, the original material properties are retained. Movement or stirring along the weld line forces the softened material from the elements towards the trailing edge, causing the adjacent regions to fuse, thereby forming a weld. FSW reduces or eliminates galvanic corrosion due to contact between dissimilar metals at end joints. Furthermore, the resultant weld retains the material properties of the material of the joined sections. Further information on FSW is disclosed in U.S. Patent Application Publication Number 2009/0308582, titled Heat Exchanger, filed on Jun. 15, 2009, which is incorporated herein by reference.

The tubes **64** and the tube sheets **68**, **72** are preferably made of the same material, such as, for example, aluminum, aluminum alloy, or marine-grade aluminum alloy. Aluminum and most of its alloys, as well as high alloy stainless steels and titanium, are amenable to the use of the FSW joining technique. The tubes and tube sheets can also be made from other materials such as metals including, but not limited to, high alloy stainless steels, carbon steels, titanium, copper, and bronze, and non-metal materials including, but not limited to, thermally enhanced polymers or thermoset plastics.

Other joining techniques can be used to secure the tubes and the tube sheets, such as expansion, press-fit, brazing, bonding, and welding (such as fusion welding and lap welding), depending upon the application and needs of the heat exchanger and the user.

In the example illustrated in FIGS. **2**-**4**, the tubes **64** are substantially round when viewed in cross-section and substantially linear from the end **66** to the end **70**. However, the shape of the tubes, when viewed in cross-section, can be square or rectangular, triangular, oval shaped, or any other shape, and combinations thereof. In addition, the tubes need not be linear from end to end, but can instead be curved, helical, and other shape deviating from linear. A total of seven tubes **64** are illustrated in this example. However, it is to be realized that a smaller or larger number of tubes can be provided.

It is preferred that the tubes be made of a material, such as a metal like aluminum, that permits extrusion or other seamless formation of the tubes. By eliminating seams from the tubes, corrosion is minimized.

The tube bundle **54** also includes a baffle assembly **80** integrated therewith. In the illustrated embodiment, the baffle assembly **80** is formed by a plurality of discrete (i.e. separate) heat transfer units **82** that are connected to each other so that the baffle assembly **80** has a substantially helix-shape that extends along the majority of the length of the tube bundle **54** around the longitudinal axis of the tube bundle. More preferably the helix-shaped baffle assembly **80** formed by the heat transfer units **82** extends substantially the entire axial length of the tube bundle.

The baffle assembly **80** increases the interaction time between the second fluid in the interior chamber of the shell and the walls of the tubes **64**. Further, as described further below, the heat transfer units **82** forming the baffle assembly are made of material that is thermally conductive, so that the baffle assembly **80** effectively increases the amount of surface area for thermal contact between the tubes and the second fluid. In addition, the substantially helix-shaped baffle assembly **80** substantially reduces or even eliminates dead spots in the interior chamber of the shell. The helix-shaped baffle assembly **80** can reduce pressure drop, reduce flow restriction of the fluid, and reduce the required force of pumping, yet at the same time provide directional changes of the second fluid to increase interaction between the second fluid and the tubes. Thus, the baffle assembly **80** provides the heat exchanger **50** with greater overall heat transfer efficiency between the second fluid and the tubes.

In an embodiment, the heat transfer units **82** can be strengthened by the use of solid or perforated plates, made from a thermally conductive material such as aluminum, affixed to the heat transfer units **82**. The plates can be affixed to the units **82** in a periodic pattern along the helix, or they can be affixed to the units in any arrangement one finds provides a suitable strengthening function. The plates can be used to assist in the assembly of the tube bundle and the heat exchanger, and can assist with minimizing the pressure drop on the shell-side flow. FIG. **18** shows an example of such a plate.

Referring to FIG. **5** together with FIGS. **2**-**4**, each heat transfer unit **82** comprises a generally wedge-shaped, planar body **84** having a generally triangular or pie-shape that has radiused inner surfaces to fit the curvature of the outer surfaces of the tubes. As described further below, the unit **82** includes a foam material such as graphite foam or metal foam. Preferably, the unit **82** consists essentially of the foam material, and more preferably consists of the foam material.

The body **84** includes a first major surface **86** and a second major surface **88** opposite the first major surface. In the illustrated embodiment, the major surfaces **86**, **88** are substantially planar. However, one or more of the major surfaces **86**, **88** need not be planar and could have contours or be shaped in a manner to facilitate fluid flow across or past the unit **82**. Fin patterns shown in FIGS. **17**A-**17**F could be used to enhance flow and heat transfer over the major surfaces **86**, **88**. The fins could extend substantially perpendicular to the surfaces **86**, **88**. Alternatively, certain edges of the body **84** could have fin patterns shown in FIG. **17**A thru **17**F to enhance flow and heat transfer from the edges of the heat transfer unit. A support rod hole **90** extends through the body **84** from the first major surface **86** to the second major surface **88** for receipt of a support rod described below. In another embodiment, an open-ended slot is used instead of the hole **90** to receive the support rod. Therefore, any opening, such as a hole or slot, could be used to receive the support rod.

The perimeter of the body **84** is defined by an arcuate radially outer edge **92** connected to linear side edges **94**, **96** at opposite ends of the outer edge. The side edges **94**, **96** converge toward a common center **98** which is removed during formation of the unit **82**. The side edges **94**, **96** terminate at radiused tube contact surfaces **100**, **102**, respectively, that are positioned on the body **84** opposite the radially outer edge **92**.

Each of the contact surfaces **100**, **102** is configured to connect to an outer surface of one of the tubes **64** for establishing thermal contact between the heat transfer unit **82** and the tubes. To maximize thermal contact, the contact surfaces **100**, **102** are configured to match the outer surface of the tubes **64**. In the illustrated embodiment, the contact surfaces **100**, **102** are curved, arcuate, or radiused to generally match a portion of the outer surface of the tubes **64**. However, the contact surfaces **100**, **102** can have any shape that corresponds to the shape of the tubes, for example square or rectangular, triangular, oval, or any other shape, and combinations thereof.

The body **84** also includes a finger section **104** that in use extends between the two tubes **64** engaged with the contact surfaces **100**, **102**. The finger section **104** includes linear edges **106**, **108** that extend from the contact surfaces **100**, **102** and that terminate at a third tube contact surface **110** that is configured to contact an outer surface of a third tube **64** for establishing thermal contact with the third tube. The contact surface **110** is configured to match the outer surface of the third tube. In the illustrated embodiment, the contact surface is slightly curved or arcuate to generally match a portion of the outer surface of the third tube. However, the contact surface **110** can have any shape that corresponds to the shape of the third tube, for example square or rectangular, triangular, oval, or any other shape, and combinations thereof. In certain embodiments, for example where contact between the body **84** and a third tube is not desired or where there is insufficient space between the tubes for the finger section to extend through, the finger section **104** can be eliminated.

FIGS. **3** and **4** show the heat transfer units **82** mounted in position on the tube bundle **54**. As shown in FIG. **3**, a plurality of support rods **120** are mounted at one end thereof to the tube sheet **72** and extend substantially parallel to the tubes **64**. The opposite ends of the support rods **120** are unsupported and not fixed to the tube sheet **68**. In another embodiment, the opposite ends of the support rods are also fixed to the tube sheet **68**. In the illustrated embodiment, four support rods **120** are provided and are evenly spaced around the tube bundle **54**. However, a larger or smaller number of support rods **10** can be used based in part on the size of the heat transfer units **82** that are used.

The heat transfer units **82** are mounted on the tube bundle **54** with the outer edges **92** thereof facing radially outward. A support rod **120** extends through the hole **90** or other opening and the tube contact surfaces **100**, **102**, **110** are in thermal contact with outer surfaces of three separate tubes **64**. When in thermal contact with the tubes, the major surfaces **86**, **88** form heat transfer surfaces that extend substantially radially from the outer surfaces of the tubes. As used herein, “in thermal contact” includes direct or indirect contact between the tube contact surfaces and the tubes to permit transfer of thermal energy between the tube contact surfaces and the tubes. Indirect contact between the tube contact surfaces and the tubes could result from the presence of, for example, an adhesive or other material between the tube contact surfaces and the surfaces of the tubes. When a hole is used, the hole **90** is preferably sized such that a relatively tight friction fit is provided with the support rod **120** to prevent axial movement of the heat transfer unit on the rod. If desired, fixation of the heat transfer unit **82** on the rod **120** can be supplemented by fixation means, for example an adhesive between the hole **90** and the rod. Instead of the hole, a slot can be formed that receives the support rod which can be secured via a friction fit or bonded using an adhesive.

If adhesive bonding is used, the adhesive can be thermally conductive. The thermal conductivity of the adhesive can be increased by incorporating ligaments of highly conductive graphite foam, with the ligaments in contact with the surfaces heat transfer unit(s) and the tubes, and the adhesive forming a matrix around the ligaments to keep the ligaments in intimate contact with the tubes and heat transfer units. The ligaments will also enhance bonding strength by increasing resistance to shear, peel and tensile loads.

As best seen in FIG. **4**, the heat transfer units **82** are arranged in a helical manner to form the baffle assembly **80**. Each heat transfer unit is axially and rotationally offset from an adjacent heat transfer unit with a small overlap region **122** between each pair of adjacent heat transfer units. Because of the overlap regions **122**, the baffle assembly formed by the heat transfer units is substantially continuous along the length of the tube bundle **54**. The amount of overlap provided in the region **122** can vary based on the size and depth or thickness of the heat transfer units. In the overlap regions **122** the adjacent heat transfer units can be secured together. For example, the heat transfer units **82** can be frictionally engaged in the overlap regions so that friction maintains the relative rotational positions of the heat transfer units. Alternatively, an adhesive or other fixation technique can be provided at the overlap regions to fix the relative rotational positions of the heat transfer units.

The periodicity of the helix can be changed by altering the angle of rotation of the heat transfer units. For example, the helix can have an angle of 30 degrees, 60 degrees, 90 degrees, 120 degrees, 150 degrees, 180 degrees and other angles. A person having ordinary skill in the art can determine the desired angles of rotation depending upon, for example, the desired performance of the heat exchanger.

In addition, as discussed above, a metal plate (FIG. **18**) can be used to strengthen the foam heat transfer units **82** and assist in fabrication of the tube bundle. The support plate can also be embedded within the foam heat transfer unit **82** during formation of the heat transfer units **82**. The metal plate secures the positioning of the tubes in a fixed pattern as an alternating baffle that travels in a helical pattern down the tube axes. The metal plate can be used to overlap two or more foam pieces to provide strength of the graphite core assembly.

When the tube bundle is installed in the shell **52**, the heat transfer units **82** are also sized such that the radially outer edges **92** thereof are positioned closely adjacent to, or in contact with, the interior surface of the shell to minimize or prevent the second fluid flowing in the shell from flowing between the radially outer edges **92** and the interior surface. This forces the majority of the fluid to flow past the tubes **64** in a generally spiral flow path defined by the heat transfer units **82**. In some embodiments, the heat transfer units **82** need not overlap, but can instead be sized and mounted so as to have gaps between adjacent heat transfer units to permit some of the fluid to flow axially between the adjacent heat transfer units.

The unit **82** (as well as the heat transfer units described below) includes, consists essentially of, or consists entirely of, a foam material such as graphite foam or metal foam. The term foam material is used herein to describe a material having closed cells, open cells, coarse porous reticulated structure, and/or combinations thereof. Examples of metal foam include, but are not limited to, aluminum foam, titanium foam, bronze foam or copper foam. In an embodiment, the foam material does not include metal such as aluminum, titanium, bronze or copper.

In one embodiment, the foam material is preferably graphite foam having an open porous structure. Graphite foam is advantageous because graphite foam has high thermal conductivity, a mass that is significantly less than metal foam materials, and has advantageous physical properties, such as being able to absorb vibrations (e.g. sound). Graphite foam can be configured in a wide range of geometries based on application needs and/or heat transfer requirements. Graphite foam can be used in exemplary applications such as power electronics cooling, transpiration, evaporative cooling, radiators, space radiators, EMI shielding, thermal and acoustic signature management, and battery cooling.

FIGS. **6**A-E depict an exemplary process of how the heat transfer units **82** can be made. It is to be realized that this process is exemplary only and that other processes can be used. The heat transfer units **82** can be made by a process that stamps a foam material into a plurality of the wedge-shaped bodies **84**. FIG. **6**A shows a die **128** for simultaneously punching a plurality of the bodies **84** from a circular foam substrate **130** (FIG. **6**D). In FIG. **6**B, the foam substrate is shown as stamped by the die. FIG. **6**C shows the stamped material being pulled up and transitioned with the press to force the foam from the die. FIGS. **6**D and **6**E show the foam pressed out of the die **128**, creating a plurality of the wedge-shaped bodies **84**. In the illustrated example, five wedge-shaped bodies **84** are formed with each stamping sequence. However, a smaller or larger number of bodies **84** can be formed if desired. A clover-leaf shaped remainder **132** is left at the center of the substrate **130** which can be discarded.

FIGS. **6**D and **6**E show the bodies **84** without the holes **90**. The holes **90** could be formed directly by the die **128**. Alternatively, if the die does not form the holes, the holes can be created in the bodies **84** after the stamping process through a separate machining process.

FIG. **7** shows another embodiment of a foam heat transfer unit **150** disposed on a tube **64** of a tube bundle of a shell-and-tube heat exchanger. The heat transfer unit **150** comprises a generally cylindrical body with a central passage through which the tube **64** extends. The heat transfer unit **150** is in thermal contact with, directly or indirectly, the outer surface of the tube **64**. The body of the heat transfer unit **150** includes opposite end surfaces **152** that form heat transfer surfaces extending substantially radially from the outer surface of the tube. The heat transfer unit **150** can be fixed on the tube to maintain the axial position thereof in any suitable manner, for example by a friction fit or by using an adhesive. Axially extending channels **154** are formed in the body that extend between the end surfaces **152**. The channels **154** are evenly circumferentially spaced from one another around the body. In the illustrated embodiment, four channels **154** are shown, although a smaller or larger number of channels **154** can be used.

In FIG. **7**, a pair of the heat transfer units **150** are shown disposed on the tube **64**, spaced from each other with an axial gap between the heat transfer units. The two heat transfer units are rotated, for example, approximately 45 degrees relative to each other. However, the rotational angle between the heat transfer units can be more or less than 45 degrees, with the angle chosen based on, for example, the number of grooves and the spacing of the heat transfer units on the tube **64**.

As shown by the arrows in FIG. **7** representing the flow of fluid, a fluid flowing through the channel **154** impacts the surface of the adjacent heat transfer unit between the channels **154** causing the fluid to change direction in order to flow into the channels **154** of the adjacent heat transfer unit **150**. Additional heat transfer units **150** can be disposed along the entire length of the tube **64**, spaced from each other and rotated relative to a preceding heat transfer unit, similar to that shown in FIG. **7**.

FIG. **8** shows an embodiment of a foam heat transfer unit **160** disposed around the tube **64** of a tube bundle of a shell-and-tube heat exchanger. The heat transfer unit **160** is configured as a cylindrical sleeve with at least one end surface **162** that forms a heat transfer surface extending substantially radially from the outer surface of the tube. The heat transfer unit **160** can extend along any length of the tube, and preferably extends along substantially the entire length of the tube. The heat transfer unit **160** can be fixed on the tube to maintain the axial position thereof in any suitable manner, for example by a friction fit or by using an adhesive. In another embodiment, the heat transfer unit **160** is formed by two or more semi-circular sections that are fixed to the outer surface of the tube to form a sleeve. In addition, the sections can be spaced from one another to form one or more grooves between the sections that extend along the axis of the tube **64**.

With each of the heat transfer units **150**, **160**, they can be used by themselves, with each other, or with the heat transfer units **82**. In addition, when the heat transfer units **150**, **160** are mounted on the tubes **64**, the outer surfaces of the heat transfer units **150**, **160** preferably are in thermal contact with, directly or indirectly, the outer surfaces of the heat transfer units **150**, **160** of one or more adjacent tubes **64**.

FIG. **9** shows an embodiment of a portion of a tube bundle **170** of a shell-and-tube heat exchanger with a plurality of tubes **172** similar in function to the tubes **64**. A plurality of identical foam heat transfer units **174** are illustrated as being engaged with the tubes **172** and spaced along the length of the tubes. The heat transfer units **174** have bodies that are constructed as cradles or frames so that each heat transfer unit **174** is configured to engage with a plurality of the tubes **172**. In particular, the body of each heat transfer unit **174** is formed with a pair of outer tube contact surfaces **176*a***, **176*b*** and three inner tube contact surfaces **178*a***, **178*b***, **178*c***. However, the heat transfer units **174** can be configured to engage with more or less tubes as well. Each heat transfer unit **174** also includes generally planar end surfaces that form heat transfer surfaces extending substantially radially from the outer surface of the tubes.

FIG. **9** shows a first set of the heat transfer units on one side of the tubes **172** with the outer contact surfaces **176*a***, **176*b*** facing upward, and a second set of the heat transfer units on the opposite side of the tubes **172** with the outer contact surfaces **176*a***, **176*b*** facing downward. The first set of heat transfer units is axially or longitudinally offset from the heat transfer units of the second set. In the embodiment illustrated in FIG. **9**, seven tubes **172** can be engaged with the heat transfer units **174**, including two tubes engaged with the tube contact surfaces **176*a***, **176*b*** of the upper set, two tubes engaged with the tube contact surfaces **176*a***, **176*b*** of the lower set, and three tubes engaged with the inner tube contact surfaces **178*a***, **178*b***, **178*c*** of the upper and lower set. It is to be realized that the heat transfer units **174** can be configured to engage with a larger or smaller number of tubes.

Depending upon the layout of the heat transfer units **174**, the heat transfer units can create offsets, spirals or other flow patterns, in either counter, co-current or cross-flow arrangements. FIGS. **17**A-F illustrate examples of patterns formed by different configurations of the foam heat transfer units **174** from FIG. **9**. For example, as shown in FIG. **17**A, the heat transfer units can be arranged into a baffled "offset" configuration. FIG. **17**B shows the heat transfer units arranged disposed in an offset configuration. When viewed from the top, each of the heat transfer units may have the shape of, but not limited to, square, rectangular, circular, elliptical, triangular, diamond, or any combination thereof. FIG. **17**C shows the heat transfer units arranged into a triangular-wave configuration. Other types of wave configurations, such as for example, square waves, sinusoidal waves, sawtooth waves, and/or combinations thereof are also possible. FIG. **17**D shows the heat transfer units arranged into an offset chevron configuration. FIG. **17**E shows the heat transfer units arranged into a large helical spiral. FIG. **17**F shows the heat transfer units arranged into a wavy arrangement or individual helical spirals.

FIG. **10**A shows another embodiment of a tube bundle that has a plurality of tubes **190** arranged with an equilateral triangular pitch (i.e. the space between the tubes is generally an equilateral triangle). FIG. **10**B shows tubes **190** of a tube bundle arranged with a square pitch, while FIG. **10**C shows tubes **190** of a tube bundle arranged with a staggered square pitch.

In FIGS. **10**A-C, foam heat transfer units **192** are shaped to fit in the pitch space between the tubes. For example, as shown in FIG. **10**A, foam heat transfer units **192** are disposed between the tubes **190** and have surfaces that are in thermal contact with the tubes. Each of the heat transfer units **192** comprises a generally triangular body, that can be radiused to the curvature of the tubes, with a generally triangular cross-section, and with the three surfaces of the triangular body in thermal contact with, directly or indirectly, three separate tubes **190**.

The heat transfer units **192** may be arranged as required for heat transfer efficiency and/or providing directional flow of the fluid outside the tubes **190**. For example, the heat transfer units **192** can be arranged in any configuration to mimic a helix, multiple helix, offset baffle, offset blocks, or other patterns as shown in FIGS. **17**A-F.

A person of ordinary skill in the art would realize that the tubes can be arranged with other pitch shapes between the tubes, and that the foam heat transfer units can have other corresponding shapes as well.

With reference to FIGS. **11** and **12**, another embodiment of a shell-and-tube heat exchanger **200** is illustrated that employs a tube bundle that includes twisted tubes **202** together with a foam heat transfer unit **204**. This embodiment has a number of advantages, including strengthening the tube core, eliminating the need for baffles, minimizing vibrations, and enhancing heat transfer on both the tube side (i.e. on the helical tubes) and on the shell side (the foam heat transfer unit).

The heat exchanger **200** includes a shell **206** that has axial inlets and outlets at each end for a first fluid to flow into and out of the tubes **202**. Tubes sheets, similar to the tube sheets **68**, **72** would be provided at each end of the tube bundle, would be attached to each tube **202**, and would fit within and close off the ends of the shell **206**. The shell also includes a radial inlet **208** and a radial outlet **210** for a second fluid.

In this embodiment, the tubes **202** are twisted helically around the foam heat transfer unit **204** along the length of the heat transfer unit **204**. The heat transfer unit **204** comprises a central, solid body of foam such that at any cross-section of the tube bundle, the foam body forms a heat transfer surface extending substantially radially from the outer surface of the tube(s). In FIG. **11**, the heat transfer unit **204** is represented by the dashed line extending the length of the shell **206**. The dashed line is not intended to imply that the heat transfer unit **204** is broken into sections or is discontinuous (although it is possible that the heat transfer unit **204** could be broken into separate section or made discontinuous if desired). The helical arrangement of tubes **202** enhances heat flow between the fluid flowing in the tubes and the fluid flowing in the shell outside of the tubes, by breaking up boundary layers inside and/or outside the tubes and combining axial and radial flow of the fluid along and around the outer surface of the tubes. In addition, the use of a baffle can be eliminated if desired. Further, the tubes **202** could be twisted about their own axes as well.

Although FIGS. **11** and **12** show six tubes **202**, a smaller or larger number of tubes can be used. For example, as discussed further below with respect to FIGS. **13-15**, three tubes can be helically wound around a central, solid heat transfer unit.

FIG. **13** is a cross-sectional view of another embodiment of a tube bundle that contains many axial tubes **222** disposed in a shell **224**. Two different implementations of the twisted or helical tube concept are illustrated. The triangle **226** in FIG. **13** illustrates three tubes **228** helically twisted about a central, solid body foam heat transfer unit **230**. This is illustrated more fully in FIG. **14** which additionally shows an optional sleeve **232** disposed around the assembly formed by the tubes **228** and the heat transfer unit **230** to form a tube-within-a-tube construction. The heat transfer unit **230** comprises a central, solid body of foam such that at any cross-section, the foam body forms a heat transfer surface extending substantially radially from the outer surface of the tube(s). In FIG. **14**, the heat transfer unit **230** is represented by the dashed line extending the length of the sleeve **232**. The dashed line is not intended to imply that the heat transfer unit **230** is broken into sections or is discontinuous (although it is possible that the heat transfer unit **230** could be broken into separate section or made discontinuous if desired).

Returning to FIG. **13**, a hexagonal arrangement **240** of the twisted tube concept is illustrated and shown more fully in FIG. **15**. In the hexagonal arrangement **240**, a tube within a tube concept is provided similar to the single arrangement shown in FIG. **14**, wherein a hexagonal pattern of six tubes-within-tubes assemblies **242** are used. Each assembly **242** includes a plurality of tubes **244**, for example three tubes, helically twisted about a central, solid body foam heat transfer unit **246**, with the tubes **244** and the heat transfer unit **246** disposed within a larger fluid carrying tube **248**. So the first fluid flows within the tubes **244** as well as within the tubes **248** in contact with the outside surfaces of the tubes **244**.

This twisted tube concept can be used by itself or in combination with any of the embodiments previously described herein. For example, FIG. **9** shows an arrangement similar to FIG. **14**, with a plurality of the tubes **228** twisted helically around the heat transfer unit **230**, and the tubes **228** and unit **230** disposed inside one of the tubes **172** to function together with the heat transfer units **174** at increasing the effectiveness of the heat exchanger.

The heat transfer units **204**, **230** have been described above as being solid bodies. However, the heat transfer units **204**, **230** need not be solid. Instead, the heat transfer units **204**, **230** can function as fluid carrying fluid distribution tubes which would be useful for creating a baffle-less design in a spray evaporator. For example, with reference to FIG. **12**, the heat transfer unit **204** can carry a fluid and be configured to spray the fluid outward as shown by the arrows onto the surfaces of the tubes **202**. The sprayed fluid exchanges heat with the tube surfaces, causing some or all of the sprayed fluid to change phase into a vapor. Likewise, as illustrated by the arrows in FIGS. **13** and **14**, the heat transfer unit **230** can be configured to spray fluid outward onto the tubes. One can also alternate foam and spray tubes too in various configurations.

FIG. **16** illustrates another embodiment of a shell-and-tube heat exchanger that uses rectangular blocks of foam heat transfer units **300** that are in thermal contact with, directly or indirectly, a plurality of axial tubes **302**. The blocks would extend some or all of the axial length of the tubes **302**. The blocks form a staggered diagonal baffle arrangement which is useful in applications where the second fluid flows in a cross-flow direction relative to the flow of the first fluid through the tubes **302**. However, other heat transfer unit configurations and arrangements, as well as other flow patterns, are possible.

All of the shell-and-tube heat exchangers described herein operate as follows. A first fluid is introduced into one axial end of the tubes of the tube bundles, with the fluid flowing through the tubes to an outlet end where the first fluid exits the heat exchanger. The tubes can be single pass or multi-pass. Simultaneously, a second fluid is introduced into the shell. The second fluid can flow counter to the first fluid, in the same direction as the first fluid, or in a cross-flow direction relative to the flow direction of the first fluid. As the second fluid flows through the shell, it contacts the outer surfaces of the tubes and/or the surfaces of the heat transfer units. Because the first fluid flows within the tubes, separated from the second fluid, heat is exchanged between the first and second fluids.

Depending upon the application, the first fluid can be at a higher temperature than the second fluid, in which case heat is transferred from the first fluid to the second fluid via the tubes and the heat transfer units. Alternatively, the second fluid can be at a higher temperature than the first fluid, in which case heat is transferred from the second fluid to the first fluid via the tubes and the heat transfer units.

The first and second fluids can be either liquids, gases/vapor or a binary mixture thereof. One example of a first fluid is water, such as sea water, and one example of a second fluid is ammonia in liquid or vapor form, which can be used in an Ocean Thermal Energy Conversion system.

The examples disclosed in this application are to be considered in all respects as illustrative and not limitative. The scope of the invention is indicated by the appended claims rather than by the foregoing description; and all changes which come within the meaning and range of equivalency of the claims are intended to be embraced therein.

The invention claimed is:

1. A shell-and-tube heat exchanger, comprising:

a shell defining an interior space, a first end, a second end, and an interior surface;

the shell including a first inlet for a first fluid, a first outlet for the first fluid, a second inlet for a second fluid, and a second outlet for the second fluid;

a tube bundle disposed in the interior space of the shell, the tube bundle including:

a plurality of tubes;

a first tube sheet fixed to first ends of the plurality of tubes, the first tube sheet is fixed to the shell adjacent to the first end thereof;

a second tube sheet fixed to second ends of the plurality of tubes, the second tube sheet is fixed to the shell adjacent to the second end thereof;

the plurality of tubes are in fluid communication with the first inlet and the first outlet so that the first fluid can flow into and through the plurality of tubes;

the second inlet and the second outlet are in fluid communication with a space defined between the first tube sheet and the second tube sheet so that the second fluid can flow into and through the space between the first tube sheet and the second tube sheet;

a helical baffle assembly connected to the plurality of tubes, the helical baffle assembly includes a plurality of wedge-shaped bodies formed of graphite foam;

each wedge-shaped body includes an arcuate radially outer edge that is in contact with the interior surface of the shell, first and second radiused tube contact surfaces positioned opposite the arcuate radially outer edge and each in contact with an outer surface of a respective one tube of the plurality of tubes, a first linear side edge extending from the arcuate radially outer edge to the first radiused tube contact surface, and a second linear side edge extending from the arcuate radially outer edge to the second radiused tube contact surface;

each wedge-shaped body is overlapped and in contact with an adjacent one of the wedge-shaped bodies over an overlap region, and each overlap region extends from the arcuate radially outer edge to the respective first and second radiused tube contact surfaces.

2. The heat exchanger according to claim **1**,

wherein central axes of the tubes of the plurality of tubes are parallel to each other.

3. The heat exchanger according to claim **1**, wherein the wedge-shaped bodies are bonded to outer surfaces of the tubes of the plurality of tubes with a thermally conductive adhesive.

4. The heat exchanger according to claim **3**, comprising conductive ligaments disposed within the thermally conductive adhesive, the conductive ligaments being in intimate contact with the outer surfaces.

5. The heat exchanger according to claim **1**, further comprising a metal plate secured to each one of the wedge-shaped bodies.

6. The heat exchanger according to claim **2**, wherein each of the wedge-shaped bodies includes a hole or slot that penetrates therethrough, and further comprising a support rod extending through the hole or slot, an axis of the support rod is parallel to the central axes of the tubes.

7. The heat exchanger according to claim **6**, further comprising:

the first ends of the tubes are joined to the first tube sheet in a manner to prevent fluid leakage between the first ends and the first tube sheet and the second ends of the tubes are joined to the second tube sheet in a manner to prevent fluid leakage between the second ends and the second tube sheet; and

the support rod has a first end joined to the first tube sheet in a manner to prevent fluid leakage between the first end thereof and the first tube sheet.

8. The heat exchanger according to claim **7**, wherein the support rod includes a second end that is joined to the second tube sheet in a manner to prevent fluid leakage between the second end thereof and the second tube sheet.

9. The heat exchanger according to claim **7**, wherein the first end and the second end of each tube are joined to the first tube sheet and the second tube sheet respectively by friction-stir welded joints, and the first end of the support rod is joined to the first tube sheet by a friction-stir welded joint.

10. The heat exchanger according to claim **1**, wherein each wedge-shaped body consists of graphite foam.

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